UCRL- 92559
PREPRINT

ECONOMIC REQUIREMENTS FOR COMPETITIVE LASER FUSION POWER PRODUCTION

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This paper was prepared for submittal to the 11th Symposium on Fusion Engineering, Austin, Texas, November 18-22, 1985.

November 15, 1985

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Abstract

An economic model of a laser fusion commercial power plant is used to identify the design and operating regimes of the driver, target and reaction chamber that will result in economic competitiveness with future fission and coal plants. We find that, for a plant with a net power of 1 GW_e, the cost of the driver must be less than \$0.4 to 0.6 B, and the recirculating power fraction must be less than 25%. Target gain improvements at low driver energy are the most beneficial but also the most difficult to achieve. The optimal driver energy decreases with increasing target technology. The sensitivity of the cost of electricity to variations in cost and performance parameters decreases with increasing target technology. If chamber pulse rates of a few Hz can be achieved, then gains of 80-100 will be sufficient, and higher pulse rates do not help much. Economic competitiveness becomes more difficult with decreasing plant size. Finally, decreasing the cost of the balance of plant has the greatest beneficial effect on economic competitiveness.

Introduction

One of the factors that will be used to judge the desirability of an ICF power plant is its economic competitiveness compared to other power sources. One of the several figures of merit that will be used to judge economic competitiveness is the projected cost of electricity (COE) from such a plant. To attempt, now, to estimate the COE of an ICF power plant, when such a plant is not likely to be built for 20-40 years, might seem like the ultimate exercise in futility. Indeed, we caution against using any of the COE's calculated in this paper in an absolute sense. However, there is value in constructing a simple economic model of a future ICF plant that can be used in relative comparisons. The model should primarily be used to identify the technical developments that would lead to the greatest reduction in COE. The model can also be used (if a great deal of care is taken) to grossly compare fusion to other future power sources. The same economic assumptions must be used in the comparison. It is for these two purposes that we have attempted, in this article, to construct such a model.

The Economic Model

The COE in ¢/kW_eh is given by

$$COE = (RC_T + M + F) / (0.0876\alpha P_n) \qquad (1)$$

where R = annual fixed charge rate (yr^{-1}),
C_T = total capital cost of the plant (\$B),
M = annual operation and maintenance cost (\$B),
F = annual fuel cycle cost (\$B),
α = plant availability factor , and
P_n = net electric power (GW_e).

The evaluation of this expression for future fission and coal plants is discussed at length in the Nuclear Energy Cost Data Base[1], which, in turn, depends heavily on the Energy Economic Data Base[2]. Based on the methods and financial parameters given in Ref. 1, the constant dollar fixed charge rate we use is 8.3%. We assume that the annual fuel cost is negligible, and that the O&M cost is 3% of C_T. Thus, the numerator of Eq. 1 is equal to $0.113C_T$. The total capital cost is 1.83 times the direct capital cost. This factor includes home and field office construction and engineering services, owners cost, a project contingency, and interest during construction in constant dollars. The fractions for these indirect costs are based on the average values for nuclear and coal plants reported in Ref. 1.

The direct capital cost of the power plant is broken into three items; the reactor, the driver and the target factory. The cost of the reactor, which includes the the fusion chamber and balance of plant, is based on the recent cost estimate for the Cascade reactor [3]. The Cascade reference design has an estimated direct capital cost of \$0.659 B at a plant thermal power of 1.670 GW_t and a gross electric power of 0.905 GW_e. The cost can be scaled to other sizes by

$$C_{rd} = C_r\ (P_t/1.67)^a \quad \$B \qquad (2)$$

where C_r is reactor cost coefficient (\$B), P_t is thermal power (GW_e), and a is the power scaling coefficient. Two cases are considered in Ref 3. The fission industry is considering lowering costs by dividing construction activities into nuclear grade and conventional grade categories. In the base case fusion reactor we also assume a combination of nuclear and conventional grade construction with the same split as for a future fission plant. However, it has been suggested, for a variety of reasons, that an ICF plant may have less nuclear grade construction than a fission plant. Therefore, in order to set an upper limit on possible cost reductions, for our second fusion case we assumed all-conventional-grade construction. The base case parameters for Eq. 2 are C_r = \$0.66 B, and a = 0.5, while the parameters for the all-conventional construction are C_r = \$0.48 B, and a = 0.8.

The direct capital cost of the driver scales with the beam energy and pulse repetition rate. It is given by

$$C_{dd} = C_d\ E_d^b\ \omega^c \quad \$B \qquad (3)$$

where C_d is driver cost coefficient (\$B), E_d is driver energy (MJ), b is energy scaling exponent, ω is the pulse rate (Hz), and c is pulse-rate scaling exponent. The base case parameters are C_d = \$0.1 B, b = 0.7, and c = 0. The cost coefficient is a goal for advanced short wavelength lasers, and the energy scaling exponent is in the range of values reported in Refs. 4 and 5. The pulse-rate scaling exponent is quite uncertain and we have set it equal to 0 for our base case.

The direct capital cost of the target factory is assumed to be a constant \$0.1 B. There are currently no definitive studies on target factory costs; this is simply a rough estimate based on analogies to current facilities that mass produce precision products; e.g., semiconductor micro-chips.

*Work performed under the auspices of the U.S. DOE by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-38.

When we speak of a certain size plant, we assume that it is the net electric power (the power deliverable to the grid), P_n, that is specified. The thermal power, which appears in Eq. 2, can be expressed in terms of P_n by considering the power balance for the plant. The net power of the plant is give by

$$P_n = P_g - P_a - P_d \tag{4}$$

where P_g is the gross electric power, P_a is the auxiliary power, and P_d is the driver power. The auxiliary power is taken as a fixed fraction (f_a) of the gross electric power,

$$P_a = f_a P_g \quad . \tag{5}$$

The driver power requirement is given by

$$P_d = P_g/\eta G M \epsilon, \tag{6}$$

where η is the driver efficiency, G is the target gain, M is the system energy multiplication factor due to neutron reactions, and ϵ is the thermal-to-electric conversion efficiency of the plant. We call the expression $\eta G M \epsilon$ the fusion cycle gain. Note that its inverse is just the power fraction recirculated to the driver.

Combining the above equations gives the net electric power as

$$P_n = P_g[1- f_a - (1/\eta G M \epsilon)] \tag{7}$$

Noting that the gross power is is equal to ϵP_t, and solving for P_t we have

$$P_t = P_n \eta G M \;/\; [(1-f_a)\eta G M \epsilon - 1] \tag{8}$$

This, then, can be inserted into Eq. 2 to give us the reactor cost in terms of the target gain when all the other parameters are fixed.

The pulse rate, which appears in Eq. 3, can be written in terms of E_d and G by noting that the pulse rate is related to the thermal power by

$$\omega = 1000 P_t/E_d G M \tag{9}$$

The factor of 1000 is needed because we are expressing E_d in MJ and P_t in GW.

The final item needed to find the COE is a relationship between the target gain G and the driver energy E_d. These gain curves are very uncertain at present, of course, since high gain has not been achieved. Very complex target implosion and burn calculations are done to estimate the shape of these curves for a variety of target concepts. The most recent target gain curves from the target physics group at LLNL have been fit by the following simple expressions. The advanced concepts curve is given by

$$G_1 = 100 + 312 \ln [(E_d + 2)/2.50], \tag{10}$$

the upper edge of the best estimates for early power plants is given by

$$G_2 = 30 + 127 \ln [(E_d + 2)/2.70], \tag{11}$$

and lower edge of the best estimates is given by

$$G_3 = 10 + 44 \ln [(E_d + 2)/3.25], \tag{12}$$

where E_d is the driver energy in MJ. Moving from the lowest gain curve, G_3, to the higher curves, G_2 and G_1, represents a progression from a class of simple target designs to classes which are technologically more advanced. We refer to this process as increasing target technology.

Combining the above cost, power balance, and gain relationships, a variety of inferences can be drawn. Our reference case parameters are P_n = 1.0 GW_e, f_a = 0.017, η = 10%, M = 1.11, and ϵ = 54%. The net power is a standard size for base load plants, the driver efficiency is a reasonable goal for advanced short wavelength lasers, and the other parameters are based on the Cascade design. Note the the electric conversion efficiency is much higher than other fusion reactor designs (see Ref. 6 for details).

Exercising the Model

First, let us consider how the relative COE for a fusion plant behaves as a function of the driver cost and the fusion cycle gain. For this we need consider only the cost and power balance equations. Fig. 1 shows how the COE depends on these two parameters. In this figure we have divided the COE for fusion by the COE for future fission plants, and have also shown the relative COE for future coal plants. The fission and coal COE's are derived from the costs given in Ref. 1 using consistent economic assumptions. Recall that the fusion cycle gain is just the inverse of the power fraction recirculated to the driver. At very low fusion cycle gains, the recirculating power fraction is high, and the size of the plant required to produce a net power of 1 GW_e is very large. This results in a high capital cost and high COE as shown in Fig. 1. The very significant knee in the curves, however, implies that once a certain minimum fusion cycle gain is obtained (about 4), additional improvements in fusion cycle gain do not result in large reductions in the COE, and reducing the driver cost is far more important. Said another way, the recirculating power fraction must be kept below 25%; but once this is achieved, further improvements can be made mostly by reducing capital costs.

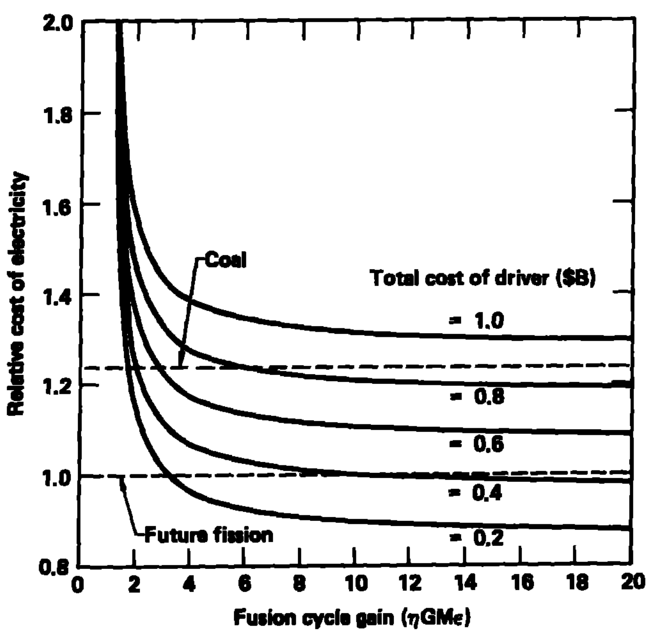

Fig. 1. Relative cost of electricity (COE) as a function of fusion cycle gain (the inverse of the recirculating power fraction) for various driver costs. Curves are for a net power (P_n) of 1 GW_e, auxiliary power fraction (f_a) of 0.017, and a thermal-to-electric conversion efficiency (ϵ) of 0.54.

The Cascade values of $M = 1.1$ and $\varepsilon = 0.54$ imply that ηG must be above about 7. The current goal for laser efficiency is 10% resulting in a minimum target gain requirement of 70. To be competitive with future fission plants, this target gain must be achieved with a driver that costs less than ~ \$0.3 B. To be competitive with future coal plants at the same gain, the driver could cost as much as \$0.7 B. In each case, if the driver cost rises very slightly, the gain required to compete rises very rapidly.

All the fundamental physics of laser fusion is contained in the target gain curves, which in our model are fit by Eqs. 10, 11 and 12. It is instructive to compare the projected target gain based on the physics to the gain required for economic competitiveness and/or to the gain required to meet certain reactor design constraints. Such comparisons can tell us which improvements will produce the greatest benefits. To do this we have overlaid three sets of curves. Fig. 2 shows an example of each type. The first, labeled "Advanced concepts target gain" in Fig. 2, is the projected target gain as a function of driver energy based on target physics calculations. Combining Eqs. 1, 2, 3, 8 and 9 will give us an expression for COE as a function of the driver energy and the target gain alone (inserting the base case values for the other variables). From this equation we can find the gain required to obtain a given COE as a function of driver energy. In Fig. 2 the curve labeled "COE = 4¢/kW$_e$h" is such a constant COE curve. Finally, one reactor design constraint is the pulse rate that is achievable in the reaction chamber. The higher the desired pulse rate, the more difficult it is to design a chamber that will recondense the vaporized material in time for the next pulse. From Eqs. 8 and 9, we can find an expression for the gain required to obtain the desired net power given an achievable chamber pulse rate. In Fig. 2 the curve labeled "Chamber pulse rate = 5 Hz" is the result of this calculation. The shaded area enclosed by the three curves defines a possible design and operating space. That is, if gains up to the advanced concepts curve and chamber pulse rates of 5 Hz prove to be achievable, then the cost of electricity will be below 4¢/kW$_e$h.

As points of reference for these graphs, the COE for future fission plants is 3.5¢/kW$_e$h and that for future coal plants is 4.4¢/kW$_e$h. That is why we have chosen to plot the COE curve for 4¢/kW$_e$h. These fission and coal COE's are based on the capital, fuel cycle and O&M costs given in Ref. 1, using the same fixed charge rate (8.3%) and availability factor (70%) as we used for the fusion plant. The COE's actually reported in Ref. 1 are somewhat higher since they assume a lower availability factor (65%), and include escalation (in excess of general inflation) during construction for the nuclear plant.

Considering the shape of the constant COE curves is instructive. As the driver energy increases, so does the driver cost. To keep the COE constant in this situation, the recirculating power must decrease by increasing gain. Just as in Fig. 1, at some point the gain necessary to do this goes to infinity. This behavior is just the opposite of the target gain curves, which are relatively flat at high driver energy and drop rapidly to zero below some threshold for each target design type.

Each of the three curves in Fig. 2, in fact, represents a family of curves that make up a grid in target gain/driver energy space. Fig. 3 shows three of the target physics curves each representing a greater achievement in terms of target technology, the three constant COE curves that bracket the future fission and coal COE's, and one of the chamber pulse rate curves. Table 1 shows three point designs that would occur at the intersections of the 5 Hz curve with the three gain curves. We note several

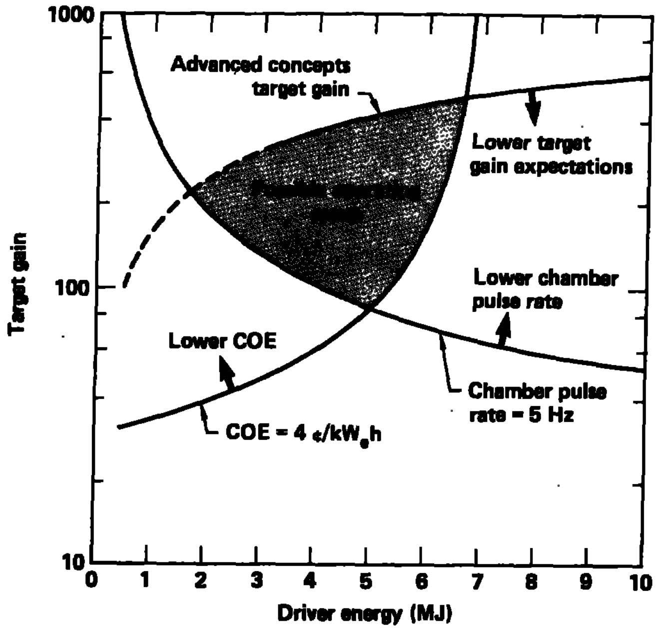

Fig. 2. Possible design and operating space for a 1 GW$_e$ ICF power plant to be competitive with future fission and coal plants. Target gain curves are defined by physics achievements, COE curves are the gain required in order to keep the COE below a prescribed value, and pulse rate curves are the gain required to achieve the desired net power at a given pulse rate.

interesting features in this figure. For any given target technology, the minimum COE will be achieved where that target gain curve is just tangent to a constant COE curve. If the tangent point lies beyond the chamber pulse rate limit, then the minimum COE will occur at the pulse rate limit.

Table 1. Base case system parameters and costs

	Target gain curve		
	Advanced Concepts	Upper edge Best est.	Lower edge Best est.
Driver energy (MJ)	1.67	3.37	7.98
Target gain	220	117	59
Target yield (MJ)	367	395	473
Pulse rate (Hz)	5	5	5
Thermal power (MW$_t$)	2039	2194	2625
Gross elec. (MW$_e$)	1105	1189	1423
Driver power (MW$_e$)	84	169	399
Auxil. power (MW$_e$)	19	20	24
Net electric (MW$_e$)	1000	1000	1000
Direct costs (\$ B)			
Reactor	0.727	0.754	0.823
Driver	0.143	0.234	0.428
Target factory	0.100	0.100	0.100
Total direct	0.970	1.088	1.351
Total cost (\$B)	1.775	1.991	2.472
COE (¢/kW$_e$h)	3.27	3.67	4.55

Examination of Fig. 3 leads to several conclusions. The first is that gain improvements at low driver energy are more beneficial than those at high driver energy. Unfortunately, the rapidly declining gain curves at low driver energy also tell us that gain improvements at low driver energy are more difficult to achieve. A second conclusion is that the COE/target technology tangent point moves to the left as we move to the higher target technology curves. That is, the optimal driver energy decreases with improving target technology. This result, of course, is highly dependent on the shape of the gain curves, which is very uncertain. Once high gain is achieved, it will be very important to determine the actual shape of the gain curves at low driver energies. Finally, Fig. 3 also tells us that if chamber pulse rates of 5 Hz or more are achievable, gains of 70-150 are sufficient to be competitive with future fission and coal plants.

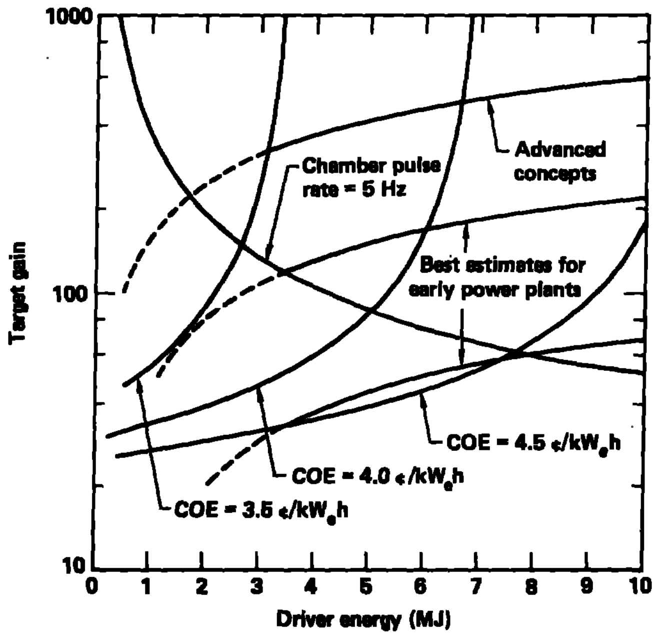

Fig. 3. The families of COE curves, target design curves and pulse rate curves identify beneficial technological improvements. Gains of 70-150 will be needed to compete with future fission (3.5¢/kW$_e$h) and coal (4.4¢/kW$_e$h) plants. Gain improvements at low driver energy are more beneficial but harder to achieve.

In Fig. 4 we examine the effect of varying the chamber pulse rate. Clearly, the higher the chamber pulse rate achievable, the lower the required gain to obtain a given COE. On the other hand, for any given target technology (e.g., the advanced concepts in Fig. 4), the target gain and COE curves are almost parallel between 5 and 10 Hz. This implies that the COE does not change rapidly as a function of chamber pulse rate in that interval, i.e., we are near the minimum anyway. Therefore, we conclude that 5 to 10 Hz pulse rates are sufficient if target gain curves are similar in shape to those we have used here. It should be noted, however, that if the gain curves turn out not to fall as rapidly as those we have used, then higher pulse rates will be more desirable and, of course, the converse is also true.

In Fig. 5 we show the effect of decreasing the cost of the balance of plant. The two curves are for the base case and the all-conventional grade construction case. Note that both the cost coefficient and the scaling exponent were changed. Reducing the coefficient flattens the curve while increasing the scaling exponent has the opposite effect. Clearly, in this case, the 33% decrease in the coefficient far outweighed the 60% increase in the exponent. This again points out the relative importance of reducing capital costs in increasing the available design and operating space.

Several other parameter variations were examined in the target-gain/driver-energy space. We also constructed several cross plots of the data. This sensitivity study is summarized in Table 2. An examination of the table supports the conclusions

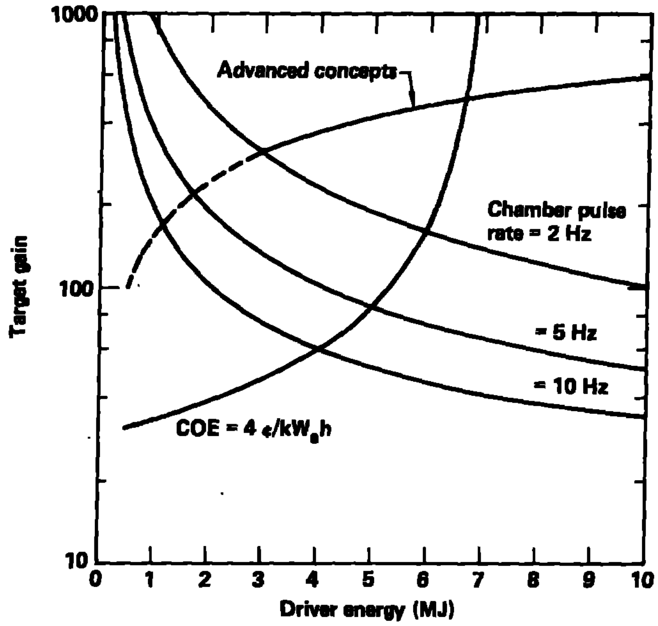

Fig. 4. Gain requirements are reduced as chamber pulse rate capability increases, but 5-10 Hz appears to be sufficient.

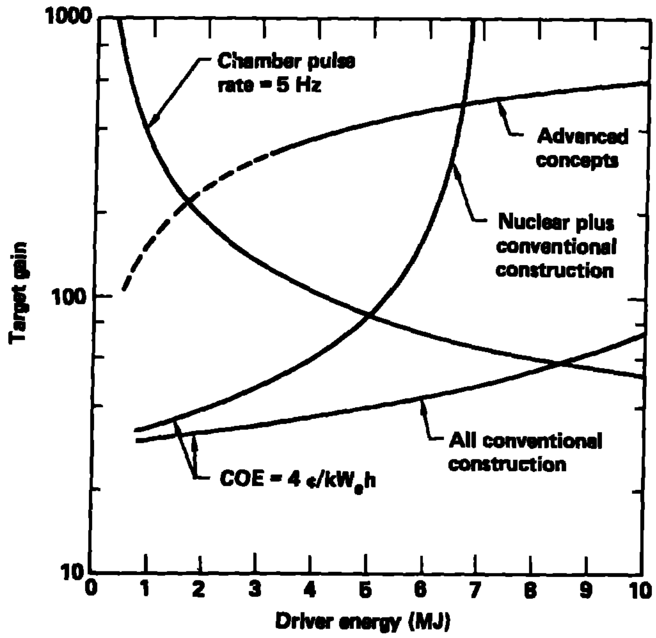

Fig. 5. Reducing the balance of plant costs increases the available operating space dramatically.

reached earlier as well as producing several new ones. In particular, it appears that decreasing the desired plant net power rapidly makes economic competitiveness extremely difficult, and that in such a circumstance the most important thing to be done is to reduce capital cost. A final inference we draw from the table is that the sensitivity of the COE to variations in cost and performance parameters decreases with increasing target technology.

Conclusions

We conclude with this simple model that an ICF power plant can be economically competitive with future fission and coal plants. To do so, the recirculating power must be kept below 25% and the driver costs must be below \$0.4 - 0.6 B (\$130-200/J) for a 1 GW_e plant. Once the recirculating power fraction is below 25%, the driver (and other) costs will dominate the problem. Several other inferences were drawn from the analysis. These are:

1. Gain improvements at low driver energy are more valuable. Based on the target physics calculations; however, high gain at low driver energy is also more difficult to achieve.
2. The optimal driver energy, and the sensitivity of the COE to variations in cost and performance parameters, decrease with increasing target technology.
3. Raising the achievable chamber pulse rate lowers the gain required for a given COE. The COE, however, is relatively insensitive to pulse rate between 5 and 10 Hz. If these pulse rates are achievable, then gains of 80 to 100 will be sufficient to be competitive.
4. Lowering the cost of the balance of plant has the greatest leverage in reducing the relative COE.
5. As the plant size (measured in terms of the net power distributed) decreases, the relative economic competitiveness becomes more difficult.

Several of these conclusions are very dependent on the shape of the gain curves. Achieving high gain initially is more likely at large driver energy. Once achieved, it will be very important to determine the true shape of the gain curves.

Table 2. Changes in the COE (¢/kW_eh) resulting from changes in the base case parameters for the three different gain curves. Base case parameters are given in square brackets. Fractional changes (%) from the base case are given in parentheses.

Parameter	Target gain: Advanced concepts	Upper edge / Best estimate	Lower edge / Best estimate
Base case	3.27 ¢/kW_eh	3.67 ¢/kW_eh	4.55 ¢/kW_eh
Reactor scaling coeff. [0.49]			
0.70	3.37 (+ 3%)	3.82 (+ 4%)	4.83 (+ 6%)
0.90	3.48 (+ 6%)	3.97 (+ 8%)	5.11 (+ 12%)
Conversion efficiency [0.54]			
0.35 (- 35%)	4.00 (+ 22%)	4.53 (+ 23%)	5.83 (+ 28%)
0.45 (- 17%)	3.56 (+ 9%)	4.01 (+ 9%)	5.04 (+ 11%)
Net power [1.0 GW_e]			
0.5 GW_e (- 50%)	4.94 (+ 51%)	5.61 (+ 53%)	7.09 (+ 56%)
1.5 GW_e (+ 50%)	2.59 (- 21%)	2.89 (- 21%)	3.56 (- 22%)
Chamber pulse rate [5 Hz]			
2 Hz	3.47 (+ 6%)	3.97 (+ 8%)	5.08 (+ 12%)
10 Hz	3.18 (- 3%)	3.56 (- 3%)	4.39 (- 4%)
Driver efficiency [0.10]			
0.05 (- 50%)	3.39 (+ 4%)	3.95 (+ 8%)	5.34 (+ 17%)
0.15 (+ 50%)	3.23 (- 1%)	3.59 (- 2%)	4.34 (- 5%)
Driver cost coefficient [\$0.10 B]			
\$0.20 B (+ 100%)	3.75 (+ 15%)	4.46 (+ 22%)	6.00 (+ 32%)
\$0.15 B (+ 50%)	3.51 (+ 7%)	4.11 (+ 12%)	5.28 (+ 16%)
Driver energy exponent [0.7]			
0.9	3.32 (+ 2%)	3.89 (+ 6%)	5.30 (+ 16%)
0.5	3.22 (+ 2%)	3.50 (- 5%)	4.07 (- 11%)
Driver pulse rate exponent [0]			
0.2	3.45 (+ 6%)	3.97 (+ 8%)	5.10 (+ 12%)
0.1	3.35 (+ 2%)	3.81 (+ 4%)	4.81 (+ 6%)

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